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On the Theory of the Moist-bulb Hygrometer. *By* JAMES APJOHN, Esq. M.D. M.R.I.A., *Professor of Chemistry in the Royal College of Surgeons.*

Read November 24, 1834.

In the number of the Edinburgh Philosophical Journal just published, and which was sent me by a friend, in consequence of its containing a report of the proceedings of the late meeting of the British Association for the promotion of science, I find an anonymous paper, entitled "Observations on the Hygrometer," which induces me to take the earliest opportunity of submitting to the Academy the following remarks.

It is well known to Meteorologists that the Hygrometers of Saussure and De Luc, and all others whose indications depend upon variations in the volume or weight of the hygroscopic substance employed, have, as philosophical instruments, been in a great measure discarded. The direct determination of the Dew-point, as it is technically called, is now almost universally practised, either according to the original method of Dalton, or by means of the elegant instrument of Professor Daniell. The method of the former, however, is much too tedious for practical purposes, and the instrument of the latter, though in principle rigorously correct, requires, in order to accuracy of result, a quickness of sight, and an adroitness in observation, which few can boast of possessing. For the great purposes, therefore, of Meteorology, the condensation Hygrometer must be considered as having, as yet, but imperfectly fulfilled the high expectations which were entertained of it.

The Dew-point process was preceded by one of an analogous description, which is said to have been first practised by Hutton the Geologist. If the bulb of a thermometer be kept covered with a thin film of water, its temperature will sink beneath that of the atmosphere, (this latter being supposed unsaturated with moisture,) the maximum depression being attained when the heat received in a given time by the film from the contiguous air is exactly equal to the caloric of elasticity of the water evaporated; and it is obvious that the amount of this depression will bear some direct ratio to the degree of dryness of the air at the time of the experiment. Further than this, however, the wet-bulb Hygrometer does not go. It affords us, for example, no information as to the exact quantity of moisture present in the surrounding atmosphere at the time of observation, because it does not indicate the position of the Dew-point. That there existed, however, between this latter and its indications, some necessary connexion, so that the one might be inferred by calculation from the other, must have been very early suspected; but Sir John Leslie, after having converted his differential thermometer into an hygrometer, was the first who attempted to point it out. In this attempt, I believe I may venture to say, he was but partially successful. I have never seen any very explicit statement of the principle on which he proceeded; but the table which he published in 1820, in his "Description of Meteorological Instruments," is undoubtedly erroneous.

In a very able article on Hygrometry in Brewster's Encyclopædia, a formula for the solution of this question is elaborately investigated; but as it is in greater part tentative, assumes, contrary to the fact, that the amount of moisture which air is capable of taking up is influenced by the pressure; and, as lastly, it does not very well accord with observations—at least some which I have made—it has been adopted, I believe, but by few Meteorologists. A satisfactory solution of this problem was still viewed as a desideratum, and of this no better proof can be given than that the "theory of the moist-bulb Hygrometer" is found among the questions submitted by the first meeting of the British Association, held at York, to the renewed consideration of philosophers.

About four months since, on turning the matter in my mind, it occurred to me that the relation between the Dew-point and the temperature of a thermometer with moistened bulb might be made matter of calculation, and deduced from the theory of mixed gases and vapours—a theory which the labours of Dalton and G. Lussac have rendered as complete as any other in Physics. It was not, however, until the latter end of August that I was enabled to return to the subject, when I succeeded in arriving, by a direct rout, at a formula derived exclusively from experimental data, and which represents with unexpected accuracy, the best observations with which I have been able to compare it. To this formula (to explain, at length, the object of this hurried communication,) I am anxious to draw, without further delay, the attention of men of science, as there is a brief notice of one for accomplishing the same object in the article of Professor Jamieson's Journal already alluded to. Of this latter, which is said to belong to Mr. Ivory, I beg to say I was altogether ignorant; nor have I yet been able to refer to the number of the Philosophical Magazine in which it is stated to have been originally published.

Having disposed of these preliminary observations, I shall now proceed to explain the principle of my method of investigation; but before doing so, I wish to observe that I would have submitted my formula to the Committee of the British Association in Edinburgh, charged with the subject of Meteorology, but that, having fallen upon it during the vacation, while sojourning in the south of Ireland, I was not able, prior to the meeting, to institute test observations myself, nor had I access to books, so as to compare it with the recorded experiments of others, on the temperature of the moist-bulb Hygrometer and the corresponding Dew-point.

When in the moist-bulb Hygrometer the stationary temperature is attained, the caloric which vaporizes the water is necessarily exactly equal to that which the air imparts in descending from the temperature of the atmosphere to that of the moistened bulb; and the air which has undergone this reduction becomes saturated with moisture. Now from these facts, and the known specific heat of air, we can calculate the weight of water m' which would be converted into vapour by the heat which a given weight of air would evolve in cooling from t the temperature of the atmosphere to t' that of the moistened bulb; and we can also calculate the total quantity of moisture m which the same weight of air would contain at t' if saturated. This being accomplished, if f' be the tension of vapour at the temperature t' $(1-\frac{m'}{m})\ f'$* $= f''$ the tension of aqueous vapour at t'' the Dew-point. Hence, by looking in Dalton's table for f'', the Dew-point is found in the opposite column.

The value of the expression $(1-\frac{m'}{m})\ f'$ may be found in the following manner:—1 being the specific heat of water, .267 (De la Roche and Berard) is that of air. Also 967° being the caloric of elasticity of steam at 212°, $212-50+967=1129°$ will be its caloric of elasticity at 50°, assuming, as is generally done, that the sum of the sensible and latent heats of vapour is the same at every temperature. One grain of air, therefore, in cooling through any number of degrees d, will raise the temperature of .267 grains of water through the same number, and will consequently be adequate to vaporize a quantity of water represented by $\frac{.267d}{1129}=\frac{d}{4195}$ grains; or, multiplying by the denominator, 4195 grains of air, in cooling through d degrees, give out the exact quantity of heat which constitutes the caloric of elasticity of d grains of vapour. But the volume of this weight of air, at 60°, and under a pressure of 30, is 13754 cubic inches; and, at the temperature t' and pressure p, $13754 \times \frac{448+t'}{508} \times \frac{30}{p} = 810\ \frac{448+t'}{p}$ cubic inches. Hence $(810 \times \frac{448+t'}{p}) \times (10{,}583 \times \frac{f'}{448+t'}$

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* This expression is obviously deduced from the fact of the tension, of vapour at a given temperature and under a given volume, being proportional to the quantity or specific gravity.

$\times , 305)^{*} = 2613.88 \times \frac{f'}{p}$ = the quantity of moisture which the air contains when saturated at t'. We will therefore have, on the principle already explained $(1 - \frac{d}{2613.88} + \frac{f'}{p}) \times f' = f' - \frac{pd}{2613.88} = f''$ the tension of vapour at the dew-point. If $p = 30$, $f' - \frac{d}{87} = f''$.

I shall now proceed to state, and subsequently observe upon, the objections which may be made to the method of investigation I have pursued. It may be said—

1°. That the air which is cooled by contact with the moistened bulb at the stationary temperature, is assumed, without proof, to be saturated with moisture.

2°. That the caloric of elasticity of steam is 1129 only at 50°.

3°. That the specific heat of air is .267 only under a pressure of 30.

4°. That the medium which is cooled from t to t' is not pure air, but a mixed atmosphere of air and vapour; and

5°. That the caloric, which at the temperature t' converts the water into vapour, is not derived exclusively from the air by contact, but partly also by radiation from surrounding bodies.

With respect to the first objection, I have only to observe, that air is an extremely bad conductor of heat, and that it is, therefore, very unlikely that the reduction of temperature which it experiences in the experiment in question can be effected in any other way than by actual contact with the moistened bulb. But, if such contact be established in the case of every indefinitely thin aerial shell, there can, I conceive, be no doubt but that each becomes charged with the full amount of moisture which belongs to its reduced temperature.

In reference to the second objection, it must of course be admitted that the caloric of elasticity of vapour varies with the temperature, and that it is represented by the number 1129 only at the temperature of 50°, a point chosen by me as being nearly the mean temperature of Dublin. In strictness, the number employed should be $967 + 212 - t'$, but it would be easy to shew that the uniform use of 1129 cannot give rise to any material error.

The third objection is usually considered as one of considerable weight. The specific heat of air varies with the pressure, and in order to accuracy of result, a proper correction must undoubtedly be made for this variation. But what is the law which it observes? Upon this point, different opinions would appear to be entertained. According, however, to De la Roche and Berard, (whose views, if not rigorously exact, are at least sufficiently so for my present purpose,) for small variations of pressure, such as occur to the natural atmosphere, the differences of specific heats under a constant volume, are proportional to the differences of pressure. And the same philosophers have shewn, that for pressures in the ratio of 1 to 1.3583, the corresponding capacities are 1 and 1.2396. Hence, as

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* $10,583 \times \frac{f'}{448 + t'} \times ,305$ = the weight of a cubic inch of vapour whose tension is f' and temperature t'.

$.3583 : .2396 :: \frac{p}{30} - 1 : \frac{x}{c} - 1$, c being the specific heat under a constant volume at 30, and x that at p,—a proportion from which we deduce

$$x = (.0223\,p + .3312)\,c.$$

But the specific heats under a constant volume, divided by the densities, give the specific heats of equal weights. And as the densities vary as the pressures directly, and as the temperatures + 448 inversely, and are, therefore, to each other in the present case as $\frac{30}{448+60}$ to $\frac{p}{448+t'}$, we will have

$$\frac{508}{30}\,c : (.0223\,p + .3312)\,c \times \frac{448+t'}{p} :: .267 : x'.$$

So that x', or the specific heat of air at temperature t' and pressure p, $= \frac{448+t'}{508} \times \frac{30}{p} \times (.0223\,p + .3312) \times .267$.

The value, therefore, of f'' already given, when subjected to this correction, will become $f' - \frac{d}{87} \times \frac{448+t'}{508} \times (.0223\,p + 3312)$.

The equation for this correction, given by the writer in the Edinburgh Philosophical Journal, is exclusively a function of p; but if the method here explained be correct, and I believe it will be found so, the temperature t' of the Hygrometer has a still greater influence on its amount. They both, however, affect it in the same direction; i. e. as they rise, it increases; and as they fall, it diminishes: so that if the one should augment as the other diminishes, they will counteract, to some extent, each other's effects. When $t' = 50$, and $p = 29$,

$$f'' = f' - \frac{d}{87} \times .958,$$

i. e. the value of the subtractive quantity is diminished by its $\frac{1}{25}$th part; but if t being still 50, p be supposed 31,

$$f'' = \frac{d}{87} \times 1.002,$$

or the subtractive term is augmented only by its $\frac{1}{500}$th part,—facts from which the general conclusion may be drawn, that when $60 - t' = 30 - p$, the latter difference being measured in tenths of an inch, and that they have opposite signs, the correction may be altogether neglected.

The theoretical justness of the fourth objection must also be conceded. The medium which is in contact with the bulb of the Hygrometer is not dry air, but air charged with the amount of vapour which belongs to the existing dew-point; and as the specific heats of air and vapour are different, this mixed atmosphere, in cooling through $t^\circ - t'^\circ$, will evidently not give out the same quantity of caloric, and can therefore not convert into vapour the same quantity of water that would be cooled and vaporized by the same weight of dry air alone. In fact, for .267, the specific heat of air, we should in strictness use the specific heat of the mixture of air and vapour; or, what will answer the same purpose, multiply by the ratio of these, the value of the quantity to be deducted from f', already obtained. Now, to determine the specific heat of the mixture, the relative weights of its constituents should be multiplied by their respective capacities, and the sum of the products divided by the sum of the weights. But the weights, being obviously as the specific gravities, are to each other as $1 : .625 \frac{f''}{p}$. Also, the specific heat of air being .267, and that of vapour .847, the former is to the latter as 1 : 3.172. Hence, according to the rule given above, we will have

$$\frac{1 + .625 \frac{f'}{p} \times 3.172}{1 + .625 \frac{f''}{p}}$$

for the specific heat of the mixture of air and vapour referred to that of dry air taken as unity; and, applying the correction as already explained, we will have an equation in which f'' is the only unknown quantity, and from which, therefore, its value may be found. The equation, however, being a quadratic, and the unknown quantity in its first dimension having a coefficient of three terms, its solution would involve tedious arithmetical operations, and can therefore not be recommended as a ready means of making the correction in question. Nor is such course at all necessary, for the same object may be achieved, and with a sufficient precision, by either assigning to f'' an average value, or by deducing approximately the tension of vapour at the dew-point by the formula $f'' = f' - \frac{d}{87} \times \frac{448 + t'}{508} (.0223\,p + .3312)$, and using the value of f'' thus obtained, in order to determine that of

$$\frac{1 + .625 \frac{f}{p} \times 3.172}{1 + .625 \frac{f}{p}}$$

the specific heat of the mixture of air and vapour. The latter method is decidedly the best; and though not mathematically accurate, will not I believe exhibit a deviation from the truth until the calculation is pushed to the seventh or eighth decimal place.

I have now to notice the last circumstance which, as far as I understand the subject, can have any influence upon the accuracy of my determination of the Dew-point.

When the wet-bulb Hygrometer has attained its stationary temperature, the caloric which it loses and gains in a given time are perfectly equal. This requires no demonstration. The caloric lost also is entirely employed in converting the water into vapour; but the whole of the acquired caloric is not necessarily derived, although such is assumed to be the case, from the air cooled by contact with the bulb of the instrument. In fact, the Hygrometer is in the predicament of a cool body placed in a warm medium, and it must consequently receive from surrounding bodies, by radiation, a greater amount of caloric than it imparts to them in virtue of the same process. To the d grains, therefore, of moisture converted into vapour by the heat given out by 4195 grains of air, in cooling through d degrees, we should add the additional quantity vaporized by the heat which the bulb has in the same time received by radiation. When $t-t'$ is small, this quantity may probably be safely neglected; but it will sometimes, I make no doubt, be of sufficient magnitude to exercise an appreciable influence. I regret my inability to assign any means of determining its amount; and shall merely add, that the neglect of this correction will always tend to render the calculated Dew-point somewhat higher than the true.

Having disposed of the theory of my method, I shall now conclude by subjecting the results which it affords to the test of experiment. I shall not at present refer to my own observations, though I have of late amassed a considerable number on the Hygrometer and Dew-point. As a more unimpeachable criterion, I shall compare my formula with the observations of others, and shall select for this purpose, it being the nearest at hand, a table published in the last number of the Edinburgh Journal. The differences, it will be seen, between the corresponding numbers of the fourth and fifth* columns of this table are so small, that we may consider them as almost entirely due to errors of observation. I may add, that as in the original table there is no notice taken of the barometer, the formula, in its most complete form, could not be applied; so that a *perfect* coincidence between calculation and observation was not in this instance to be expected.

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* The numbers in the fourth column are the observed, and in the fifth the calculated dew-points.

	t	t'	t'' Observed.	t'' Calculated.		t	t'	t'' Observed.	t'' Calculated.
1	68.25	61.75	57.25	57.5	20	64.75	58.75	53.75	54.4
2	56.25	54.5	53.25	53	21	59	54	50	49.9
3	64.5	59	54 5	55	22	63.75	57.75	53.75	53.1
4	67.5	61.25	55.75	57	23	63.5	57.25	52.25	52.5
5	67.25	61.	56.75	56.75	24	59.75	54.75	49.25	50.5
6	63	59.	56.25	56.2	25	62.5	56.25	51.25	51.25
7	62.25	57.75	55.25	54.4	26	61.25	56.5	53.25	52.75
8	68	61.75	57.25	57.2	27	60.75	56.5	53.25	53.25
9	63.25	59	56.5	56	28	62.75	57.75	53.75	54
10	69.5	63	58.25	58.75	29	65.5	60.5	55.75	57.1
11	68.75	61	56.25	55.66	30	64.75	61	58.25	58.5
12	63.5	58	54.75	53.8	31	62 5	57.25	52.75	53.2
13	63.75	58	54.5	53.6	32	62.25	56.75	52.75	5 .
14	68	61.25	56.25	56.6	33	60.25	56.5	53.75	53.3
15	69	62	57.25	57.4	34	57.25	53.75	51.5	50.33
16	66.5	61	57.5	57.3	35	57.25	53.75	51	50.33
17	66.25	61	57.5	57.5	36	58.5	54	50.75	50.25
18	67	59.5	54.5	54	37	57.25	55.25	54	53.66
19	64.5	58.75	54.25	54.5	38	67.5	59	58.75	59
								54.40	54.74